

# **CHARACTERIZATION OF DRAW SOLUTION IN FORWARD OSMOSIS PROCESS FOR THE TREATMENT OF SYNTHETIC RIVER WATER**

**RYAN YEO WHYE SEONG**

Thesis submitted in partial fulfilment of the requirements  
for the award of the degree of  
Bachelor of Chemical Engineering

**Faculty of Chemical & Natural Resources Engineering  
UNIVERSITI MALAYSIA PAHANG**

JANUARY 2014

©RYAN YEO WHYE SEONG (2014)

## ABSTRACT

Forward osmosis is a process that depends on the concentration gradient and also osmotic potential to treat water which is currently, applicable in many industries. The main factor which affects the entire process of forward osmosis is the draw solution as draw solution acts as the driving force which drives water to pass through semi-permeable membrane by means of concentration gradient. This research focuses on the characterization of draw solution in order to provide the optimum effect in treating river water in Malaysia. Apart from that, this research used synthesized river water which consists of 15mg/L of humic acid to replace river water as feed solution. This research was done so as to fill the inadequate amount of research done on forward osmosis where river water was used as feed solution. This research was conducted based on two parameters which will impact the water flux and performance of draw solution namely, concentration of draw solution and also osmotic pressure of draw solution. Thus, 4 different draw solutions made up of inorganic salt, fertilizers and organic salts were tested based on 5 different concentrations. This research also measures the humic acid rejection for each draw solution by using UV-vis spectrometer. Besides, reverse salt diffusion caused by different draw solution was also tested in terms of conductivity to determine the best performing draw solution. This research was conducted by using polyamide coated ultrafiltration membrane to separate the feed and draw solution and the permeation module was constructed as the preliminary laboratory work. Based on the results obtained, increase in molarity of draw solution is proportional to the increase in flux of water. The water flux obtained by using related formula showed the highest figure with calcium nitrate at  $2.7 \times 10^{-4} \text{ m}^3/\text{m}^2.\text{s}$  at 1mol/L, whereas the lowest flux obtained was by fructose with the reading of  $2.529 \times 10^{-5} \text{ m}^3/\text{m}^2.\text{s}$ . Besides that, calculation shows that the increase in draw solution concentration causes a decrease in humic acid rejection. However, the data recorded showed that every draw solutions at concentrations of 0.1mol/L to 1mol/L have good humic acid rejection at approximately 100%. On the other hand, sodium chloride showed higher reverse salt diffusion than calcium nitrate and the value of reverse salt diffusion increases as the molarity increases. Based on the discussions, it is found that this research showed calcium nitrate at 1mol/L as the best performing draw solution in treating river water. This research can further assist future research on forward osmosis of treating river water by narrowing down the type of draw solution that can provide best efficiency in treating river water and also show the category of draw solution which provides best efficiency.

## ABSTRAK

Osmosis hadapan adalah satu proses yang bergantung kepada kecerunan kepekatan untuk merawat air yang digunapakai dalam banyak industri. Faktor utama yang memberi kesan kepada keseluruhan proses osmosis hadapan adalah larutan penarik yang bertindak sebagai daya penggerak yang mendorong air melalui membran separa telap. Kajian ini memberi tumpuan kepada pencirian larutan penarik untuk memberikan kesan yang optimum dalam merawat air sungai. Selain itu, kajian ini menggunakan air sungai disintesis yang terdiri daripada 15mg/ L asid humik untuk menggantikan air sungai sebagai larutan suapan. Kajian ini dilakukan bagi mengisi jumlah penyelidikan berkaitan yang pada masa kini, tidak mencukupi. Kajian ini telah dijalankan berdasarkan kepada dua parameter yang akan memberi kesan fluks air dan prestasi larutan penarik iaitu kepekatan larutan penarik dan juga tekanan osmosis larutan penarik. Oleh itu, 4 larutan penarik terdiri daripada garam bukan organik, baja dan garam organik telah diuji berdasarkan 5 kepekatan yang berbeza. Kajian ini juga mengukur asid humik penolakan bagi setiap larutan penarik dengan menggunakan Uv-vis spektrometer. Penyebaran garam terbalik yang disebabkan oleh larutan penarik berbeza juga diuji dari segi kekonduksian untuk menentukan larutan penarik berprestasi terbaik. Kajian ini dijalankan dengan menggunakan poliamida bersalut membran ultrafiltration untuk memisahkan larutan suapan dan larutan penarik dan modul penyerapan itu dibina ketika kerja makmal preliminari. Fluks air diperolehi dengan menggunakan formula yang berkaitan menunjukkan angka tertinggi dengan kalsium nitrat pada  $2.7 \times 10^{-4} \text{ m}^3/\text{m}^2.\text{s}$  di 1mol/L, manakala fluks yang paling rendah diperolehi adalah dengan fruktosa dengan bacaan  $2.529 \times 10^{-5} \text{ m}^3/\text{m}^2.\text{s}$ . Selain itu, pengiraan menunjukkan bahawa peningkatan dalam kepekatan larutan penarik menyebabkan kurangnya penolakan asid humik. Tetapi, data yang direkodkan menunjukkan bahawa setiap larutan penarik pada kepekatan 0.1mol/L untuk 1mol/L mempunyai penolakan asid humik yang baik pada kira-kira 100%. Sebaliknya, natrium klorida menunjukkan penyebaran garam lebih tinggi terbalik daripada kalsium nitrat dan nilai terbalik penyebaran garam bertambah apabila kenaikan kemolaran. Berdasarkan perbincangan, didapati bahawa kalsium nitrat di 1mol/L adalah larutan penarik berprestasi terbaik dalam merawat air sungai. Kajian ini boleh terus membantu kajian akan datang yang berkaitan dengan mengurangkan jenis larutan penarik yang boleh memberikan kecekapan yang terbaik dalam merawat air sungai dan juga menunjukkan kategori larutan penarik yang menyediakan kecekapan yang terbaik .

## TABLE OF CONTENTS

SUPERVISOR'S DECLARATION .....	IV
STUDENT'S DECLARATION .....	V
<i>Dedication</i> .....	VI
ACKNOWLEDGEMENT .....	VII
ABSTRACT .....	VIII
ABSTRAK .....	IX
TABLE OF CONTENTS .....	X
LIST OF FIGURES .....	XII
LIST OF TABLES .....	XIV
LIST OF ABBREVIATIONS .....	XV
LIST OF ABBREVIATIONS .....	XVI
1 CHAPTER 1 .....	1
INTRODUCTION .....	1
1.1 Background .....	1
1.2 Motivation .....	3
1.3 Problem statement .....	4
1.4 Objective .....	5
1.5 Scope .....	5
1.6 Organisation of this thesis .....	6
2 CHAPTER 2 .....	8
LITERATURE REVIEW .....	8
2.1 Overview .....	8
2.2 Theory of treatment methods .....	8
2.2.1 Forward osmosis .....	8
2.2.2 Pressure retarded osmosis .....	9
2.2.3 Reverse Osmosis .....	10
2.2.4 Differences between forward osmosis, reverse osmosis and pressure retarded osmosis .....	11
2.2.5 Advantages of forward osmosis .....	13
2.3 Concentration polarization of forward osmosis .....	15
2.3.1 External concentration polarization .....	15
2.3.2 Internal concentration polarization .....	16
2.3.3 Influence of internal concentration polarization .....	18
2.4 Reverse salt diffusion in forward osmosis .....	18
2.5 Cellulose triacetate membrane for forward osmosis .....	19
2.6 Humic acid .....	21
2.7 Properties of draw solution in forward osmosis process .....	22
2.7.1 Osmotic pressure .....	22
2.7.2 Diffusion coefficient .....	23
2.7.3 Molecular weight .....	23
2.7.4 Concentration .....	24
2.7.5 Temperature .....	24
2.7.6 Recovery of draw solution .....	25
2.8 Past research on performance of draw solution in forward osmosis process .....	26

2.9	Recent application of forward osmosis process .....	27
2.9.1	Desalination.....	27
2.9.2	Wastewater treatment .....	29
2.9.3	Liquid and food concentration .....	29
2.10	Summary .....	30
3	CHAPTER 3 .....	31
	MATERIALS AND METHODS .....	31
3.1	Overview .....	31
3.2	Chemicals .....	31
3.3	Preparation of Membrane .....	31
3.4	Preparation of draw solution .....	32
3.5	Preparation of synthesized river water by using humic acid.....	32
3.6	Permeation module .....	32
3.7	Methodology .....	33
3.8	Summary.....	35
4	CHAPTER 4.....	36
	RESULTS AND DISCUSSION .....	36
4.1	Overview .....	36
4.2	Average time taken to reach desired volume .....	36
4.2.1	Sodium Chloride .....	36
4.2.2	Calcium Nitrate .....	37
4.2.3	Calcium Chloride .....	39
4.2.4	Fructose .....	40
4.3	Discussion and comparison of flux for each draw solutions .....	41
4.3.1	Discussion of flux for each draw solutions .....	41
4.3.2	Comparison of draw solutions' flux .....	43
4.3.3	Validity of data obtained .....	45
4.4	Humic acid rejection.....	48
4.5	Reverse salt diffusion.....	53
4.6	Selection and characterisation of best draw solution .....	54
4.7	Chapter summary .....	55
5	CHAPTER 5.....	56
	CONCLUSION AND RECOMMENDATION .....	56
5.1	Conclusion .....	56
5.2	Recommendation.....	57
	REFERENCES.....	58
	APPENDICES .....	66

## LIST OF FIGURES

Figure 2-1: Process Model of forward osmosis (Duranceau, 2012). .....	9
Figure 2-2: Process Model of pressure retarded osmosis (Cath et al., 2006).....	10
Figure 2-3: Process Model of reverse osmosis (Duranceau, 2012). .....	11
Figure 2-4: Water flux direction of forward osmosis, pressure retarded osmosis and reverse osmosis (Chou et al., 2012).....	12
Figure 2-5: Energy consumption/production of forward osmosis, pressure retarded osmosis and reverse osmosis (Chou et al., 2012). .....	13
Figure 2-6: Potential benefits of forward osmosis in water treatment (Zhao et al., 2012). .....	14
Figure 2-7: Illustration of driving force profiles, expressed as water chemical potential for osmosis through several membrane types and orientations. (a) Asymmetric dense membrane. (b) An asymmetric membrane with the porous support layer facing the feed solution which illustrates concentrative internal polarization. (c) An asymmetric membrane with the dense active layer facing the feed solution which illustrates dilutive internal polarization (McCutcheon et al., 2006).....	17
Figure 2-8: (a) Concentrative internal concentration polarization (b) Dilutive concentration polarization (McCutcheon et al., 2006). .....	17
Figure 2-9: Schematic diagram for the process of reverse salt diffusion in forward osmosis (Yong et al., 2012).....	19
Figure 3-1: Permeation module for forward osmosis (Low, 2010).....	33
Figure 3-2: Schematic diagram of the laboratory scale forward osmosis setup (Low, 2010).....	34
Figure 4-1: Graph of average time taken (Min) for sodium chloride draw solution against molarity .....	36
Figure 4-2: Graph of average time taken (Min) for calcium nitrate draw solution against molarity .....	38
Figure 4-3: Graph of average time taken (Min) for calcium chloride draw solution against molarity .....	39
Figure 4-4: Graph of average time taken (Min) for fructose draw solution against molarity .....	40
Figure 4-5: Graph of flux across membrane against molarity of draw solution.....	41
Figure 4-6: Graph of osmotic pressure for each draw solution against molarity .....	43
Figure 4-7: Trend line and regression coefficient for calcium nitrate flux.....	46
Figure 4-8: Trend line and regression coefficient for sodium chloride flux .....	46
Figure 4-9: Trend line and regression coefficient for calcium chloride flux .....	47
Figure 4-10: Trend line and regression coefficient for fructose flux.....	47
Figure 4-11: Absorption against concentration of draw solution.....	49

Figure 4-12: Graph of humic acid concentration in draw solutions against concentration of draw solution.....	50
Figure 4-13: Graph of humic acid rejection against concentration of draw solution....	51

## LIST OF TABLES

Table 2-1: Summary of draw solution and the recovery and reconcentration methods (Chekli et al., 2013). .....	26
Table 4-1: Table of average time taken for sodium chloride .....	37
Table 4-2: Table of average time taken for calcium nitrate .....	37
Table 4-3: Table of average time taken for calcium chloride.....	39
Table 4-4: Table of average time taken for fructose .....	40
Table 4-5: Table of flux for each draw solutions .....	42
Table 4-6: Van Hoff's factor for each draw solution. ....	43
Table 4-7: Line equation and regression coefficient for each draw solutions .....	48
Table 4-8: Table of humic acid absorption.....	48
Table 4-9: Table of humic acid concentration in permeate side .....	50
Table 4-10: Table of humic acid rejection .....	51
Table 4-11: Table of conductivity for sodium chloride draw solution feed side.....	53
Table 4-12: Table of conductivity for calcium nitrate draw solution feed side .....	53



## LIST OF ABBREVIATIONS

$J_w$	water flux
$A$	water permeability
$\Delta P$	hydrostatic pressure
$W$	energy consumption
$C_D$	concentration of the solute in the draw solution
$J_s$	reverse flux of the solute
$C_F$	bulk feed solution concentration
$t_s$	support layer thickness
$t_A$	active layer thickness
$C_D^m$	draw solute concentration in solution at the support layer side
$C_F^m$	draw solute concentration in solution at the boundary layer side
MW	molecular weight of solute
$n$	the number of moles of species
$R$	gas constant
$c$	solute concentration
$K$	solute resistance
$t$	thickness
$\tau$	tortuosity
$D_s$	diffusion coefficient
$\Delta V$	volume of water which permeates through the membrane
$A$	effective area of the membrane
$\Delta t$	time taken in minutes
$M$	Molarity
$J$	Van't Hoff factor

### *Greek*

$\Delta\pi$	Change in osmotic pressure
$\Delta\pi_m$	Osmotic pressure difference across the membrane
$\Delta\pi_{eff}$	Effective osmotic pressure driving force
$\delta$	external boundary layer of thickness
$\varepsilon$	porosity

### *Subscripts*

<i>eff</i>	effective
<i>max</i>	maximum

## **LIST OF ABBREVIATIONS**

DS	Draw solution
FO	Forward osmosis
HTI	Hydration Technology Inc.
MD	Membrane distillation
MPD	Metaphenylenediamin
NF	Nanofiltration
RO	Reverse osmosis
TMC	Trimesoly Chloride
UF	Ultrafiltration

# CHAPTER 1

## INTRODUCTION

### *1.1 Background*

In this current era, water treatment is one of the most vital fields which provides human with clean water to be consumed daily. In conjunction to that, many viable methods of water treatment in producing clean consumable water has been developed over the years to drastically decrease the cost and energy needed in addition of reducing any negative impacts it may cause to the environment. Among other researched water treatment methods, the method at which osmosis acts as the fundamental concept fits the current objectives of reducing cost, energy and environmental issues during the production of clean consumable water. Osmosis is a physical phenomenon that has been extensively studied by scientists in various disciplines of science and engineering. Early researchers studied the mechanism of osmosis through natural materials, and from the 1960s, special attention has been given to osmosis through synthetic materials.

Osmosis is a physical phenomenon that has been exploited by human beings since the early days of mankind. Early cultures realized that salt could be used to desiccate foods for long term preservation (Cath et al., 2006). In saline environments, most bacteria, fungi, and other potentially pathogenic organisms become dehydrated and die or become temporarily inactivated because of osmosis. Conventionally, osmosis is defined as the net movement of water across a selectively permeable membrane driven by a difference in osmotic pressure across the membrane (Cath et al., 2006). A selectively permeable membrane allows passage of water, but rejects solute molecules or ions. Present day applications of the osmosis phenomenon extend from water treatment and food processing to power generation and novel methods for controlled drug release (Cath et al., 2006).

Following the progress in membrane science in the last few decades, especially for reverse osmosis applications, the interests in engineered applications of osmosis has

been spurred (Cath et al., 2006). The further development in this field of osmosis has brought to a newer form of water treatment process also known as forward osmosis. Osmosis, or as it is currently referred to as forward osmosis, has new applications in separation processes for water treatment, food processing, and seawater/brackish water desalination. Other unique areas of forward osmosis research include pressure retarded osmosis for generation of electricity from saline and fresh water and implantable osmotic pumps for controlled drug release (Cath et al., 2006). Unlike reverse osmosis where hydraulic pressure is required, forward osmosis process simply uses the intrinsic osmotic pressure differential between the two solutions of different osmotic potential (highly concentrated draw solution and saline feed water) separated by a semi-permeable membrane to desalinate water.

Although literatures on forward osmosis membrane fouling are still scarce, recent studies indicate that, membrane fouling may not be a significant issue for forward osmosis process, which is another significant advantage for forward osmosis over reverse osmosis process. In the absence of hydraulic pressure, membrane fouling during forward osmosis process is reported to be physically reversible indicating that chemical cleaning may not be essential for forward osmosis process like in reverse osmosis process. Although the novel concept of forward osmosis was developed as early as 1968 (Popper et al., 1968), it has not been able to advance mainly due to lack of suitable forward osmosis membranes and lack of suitable draw solution. The current asymmetrical membranes used for pressure based filtration result in concentration polarization effects that severely decrease the net osmotic pressure between the two solutions and hence lower the water flux across the membrane (Tang et al., 2010). While external concentration polarization that occurs on the membrane surface can be mitigated using crossflow, similar to pressure based membrane filtration system such as reverse osmosis, internal concentration polarization occurs within the porous support layer of the asymmetrical membranes and therefore cannot be mitigated (Cath et al., 2006). Internal concentration polarization is exclusive to forward osmosis process and is said to be mainly responsible for much lower water flux achieved in forward osmosis process than the expected or theoretical water flux (Gray et al., 2006). Several significant research breakthroughs have been however reported recently in the forward osmosis membrane fabrication particularly with thin film composites and also carbon

nanotube membranes that may provide lower concentration polarization effects (Yip et al., 2010).

Since the forward osmosis process works based osmotic pressure, one of the most important components which needs to be present to enable the process of forward osmosis to occur efficiently is known as draw solution. Draw solution, also known as osmotic agent, osmotic media, brine or driving solution is the concentrated solution present in the permeable side of the membrane which acts as the source of driving force in forward osmosis process (Cath et al., 2006). There are many criterions such as osmotic pressure, water solubility and molecular weight which need to be considered in the selection of draw solution to enable the process of forward osmosis to run at optimum performance (Cath et al., 2006). Various chemicals including fertilizers had been suggested and tested as solutes of draw solution. Consequently, the results from the test done show that the selection of draw solution ranges from any organic to any inorganic materials depending on the type of feed for which water needs to be drawn.

## ***1.2 Motivation***

The world population is growing rapidly while the problems associated with a lack of fresh water is becoming a known fact affecting drinking water supplies, energy, food production, industrial output, and the quality of our environment ultimately undermining the economies of the world at large (Whetton et al., 1993). Water is also essential for improving the productivity of agricultural land to meet the world's increasing food demand; however, fresh water scarcity is a serious issue in many parts of the world. Water shortages are further exacerbated by the impact of climate change resulting in frequent drought and unpredictable rainfall events (Whetton et al., 1993).

In Malaysia, river water plays an important role in providing water to citizens and also to the environment. However, despite holding such important position in providing clean consumable water to Malaysia citizens, the majority of the river water present in Malaysia is researched and found to contain low pH value which indicates that the river water in Malaysia is acidic (Katimon et al., 2010). As a result to that, the river water in Malaysia needs to be treated correctly at low cost and energy before distributing it to the citizens. Among many water treatment methods, osmosis is the most common method used in desalination of water. For this research, forward osmosis was chosen over

reverse osmosis as the process to treat river water due to the fact that the process of reverse osmosis has high cost, high energy consumption and has limited recovery which is roughly about 30%-50% (Liu et al., 2009). On the other hand, the process of forward osmosis can be done at lower cost, energy and also has higher recovery rate (McGinnis & Elimelech, 2008).

Besides that, forward osmosis is an emerging technology that consists of an osmotically driven membrane technology where the treatment process occurs as accordance to the difference in osmotic pressure between the draw solution and feed solution which is separated by a semi permeable membrane (McGinnis & Elimelech, 2008). This further brings forward osmosis to another advantage where the absence of hydraulic pressure could potentially reduce membrane fouling and toxicity effects of product water (Suh & Lee, 2013). In spite of that, studies done on suitable draw solution for the process of forward osmosis thus far has only be revolving around seawater or brackish water as the feed solution and the research of suitable draw solution used to treat river water has been scarce and lesser still when it comes to river water in Malaysia.

Apart from that, it has been over forty years where the study of suitable inorganic draw solution has been done to for the desalination of seawater but the study of organic draw solution such as glucose has been in scarcity and fewer still the study of organic draw solution with river water as the feed solution. In addition, challenges now are also mostly related to separation and recovery of the draw solution from desalinated water. The success of forward osmosis desalination in the future especially for drinking purposes, will rely mainly on how easily and efficiently the draw solution can be separated and recovered from the desalinated water. Under all these. circumstances, the selection of suitable draw solution of either inorganic or organic for the process of forward osmosis where Malaysia river water acts as the feed solution remains skeptical to the industries, researches and students until today.

### ***1.3 Problem statement***

The following are the problem statements of this research:

- 1) Conventional treatment failed to treat water up to drinking water level.
- 2) Reverse osmosis is promising technology but too expensive.

- 3) Alternatively, new technology namely forward process could be used. However no studies reported on specific draw solution for treatment of Malaysia river water.

### ***1.4 Objective***

To determine the water flux of each draw solutions of different osmotic pressure at different concentration where humic acid was used as synthesized river water as feed solution, to determine the final concentration of humic acid in the product acquired, to determine the reverse salt diffusion of each draw solution and also to determine the most suitable draw solution which can be used to treat river water.

### ***1.5 Scope***

This research was done based on 4 solutes which were used to form the desired draw solutions. The solutes used can be categorized into 3 groups which are inorganic, organic and fertilizers. For inorganic solutes, sodium chloride was used. On the other hand, for organic, fructose this was used. Whereas, calcium nitrate was categorized under fertilizer. For feed solution, synthesized river water made of only humic acid was used due to the fact that it is the main and most abundant acidic component present in Malaysia's river water.

This research discussed on the preparation of polyamide coated ultrafiltration membrane and characteristics each draw solutions which will affect the efficiency of forward osmosis process. The characteristics include molecular weight, osmotic pressure, concentration, diffusivity, recovery process and also cost. In addition, comparison between other different treatment method including pressure retarded osmosis and reversed osmosis were discussed in the literature review part. Apart from that, the effect of internal concentration polarization and also external concentration polarization were discussed in the literature review part.

Besides that, this research was also completed by performing experiments which provided the water flux of water across the membrane for each draw solutions to determine the most efficient draw solution for synthesized river feed solution. The parameter which were experimented and calculated is the concentration and osmotic pressure of draw solution.

Water flux of desired solution across the membrane from feed solution to the draw solution will determine the efficiency and also the performance of the draw solution used and will ultimately help in determining the better draw solution to be used in forward osmosis process for river water.

The content of the product was tested with UV-vis spectrometer to determine how acceptable the product is to be drinkable to human being.

## ***1.6 Organisation of this thesis***

The structure of the reminder of the thesis is outlined as follow:

Chapter 2 provides a description on the different method of osmosis currently used this era. Besides that, this chapter also discusses on the differences between all these 3 osmosis method and the advantages of using forward osmosis method. This chapter also discusses on the problem faced by forward osmosis known as concentration polarization and reverse salt flux diffusion. In addition, this chapter also discusses on the common membrane used for forward osmosis process known as cellulose triacetate membrane and also the discussion on the humic acid is also done as it is the feed solution for this research. The most important part which is the characteristics of draw solution which affects the forward osmosis process is also discussed on this chapter. Moreover, past research on different performance of draw solution used for desalination is also reviewed under this chapter. Lastly, the common applications of forward osmosis is also discussed in this chapter.

Chapter 3 provides description on the chemicals which was used to form the draw solution. Besides that, this chapter also discussed on the preparation of membrane which was used to perform the experiment in addition to the description on the specification of materials needed to construct the permeation module. This chapter also gives description on the tabulation of data obtained to enable the performance of forward osmosis with different draw solution under the parameter of osmotic pressure and concentration to be evaluated in the result. Besides that, this chapter also discussed on the method of evaluating the performance of forward osmosis for synthesized river water formed by humic acid.



Chapter 4 discusses on the experimental data which was obtained. This chapter discussed on the performance of draw solution by means of water flux from feed to permeate side, humic acid rejection and also reverse salt diffusion. Besides, this chapter also discussed on the best performing draw solution in treating river water.

## CHAPTER 2

### LITERATURE REVIEW

#### ***2.1 Overview***

This chapter discusses and compares on the type of water treatment methods which is relatively close to the concept of forward osmosis, namely, pressure retarded osmosis and reverse osmosis. Besides that, this chapter also discusses on the advantages of using forward osmosis in water treatment over the other two methods. Moreover, this chapter also discusses on the two main problems faced by forward osmosis membrane known as concentration polarization and reverse flux diffusion which can gravely affect the efficiency of the process. Apart from that, this chapter also reviews on the properties of cellulose triacetate membrane which makes it a suitable membrane for forward osmosis membrane. A review on humic acid is also present in this chapter as it is the main feed solution which was used for this study. In addition, this chapter also discusses on all of the main characteristics such as osmotic pressure, concentration, diffusion coefficient, molecular weight and temperature of draw solution inclusive of the recovery of draw solution which will effectively affect the performance and efficiency of the forward osmosis process. This chapter also reviews on the draw solutions used by past researches and their respective performance. Lastly, this chapter reviews on the recent application of forward osmosis in the field of desalination, wastewater treatment and also food concentration.

#### ***2.2 Theory of treatment methods***

##### **2.2.1 Forward osmosis**

According to Cath et al. (2006), osmosis is the transport of water across a selectively permeable membrane from a region of higher water chemical potential to a region of lower water chemical potential. It is driven by a difference in solute concentrations across the membrane that allows passage of water, but rejects most solute molecules or ions. Osmotic pressure ( $\pi$ ) is the pressure which, if applied to the more concentrated

solution, would prevent transport of water across the membrane. Moreover also according to Cath and Childress (2006), forward osmosis uses osmotic pressure differential ( $\pi$ ) across the membrane, rather than hydraulic pressure differential which is the concept used in reversed osmosis, as the driving force for transport of water through the membrane. The forward osmosis process results in concentration of a feed stream and dilution of a highly concentrated stream also known as draw solution. The process of forward osmosis occurs in a compartment where two solutions known as feed solution and draw solution are separated by a semi-permeable membrane. Besides that, in forward osmosis, the impaired water also known as the feed solution is in contact with the dense side of a semi-permeable membrane and a highly concentrated draw solution is in contact with the support side of the membrane. The illustration of forward osmosis process is in the figure 2-1 (Achilli et al., 2010).

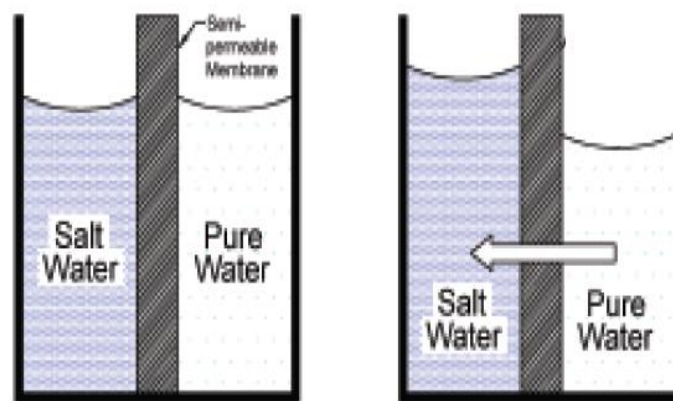


Figure 2-1: Process Model of forward osmosis (Duranceau, 2012).

### 2.2.2 Pressure retarded osmosis

Pressure retarded osmosis can be viewed as an intermediate process between forward osmosis and reverse osmosis, where hydraulic pressure is applied in the opposite direction of the osmotic pressure gradient which is similar to reverse osmosis. However, the net water flux is still in the direction of the concentrated draw solution which is rather similar to forward osmosis. This is further supported by She et al. (2013), who also stated that pressure retarded osmosis is an osmotically driven membrane process due to the water which flows from a low osmotic pressure feed solution to a high osmotic pressure draw solution against a hydraulic pressure. This process converts the osmotic power into a mechanical energy, whose power is equal to the product of water permeation rate and applied hydraulic pressure (Loeb, 1976). The mechanical energy

can be subsequently converted to other forms of useful energy (e.g., electricity by running the pressurized draw solution through a hydro turbine) (Loeb, 1976). In pressure retarded osmosis, the porous support layer faces the feed solution and the active layer of the membrane faces the draw solution. The chemical potential which is determined by the osmotic pressure difference across membrane is the effective force making energy and fresh water (She et al., 2013). The process of pressure retarded osmosis can be seen as in the figure 2-2.

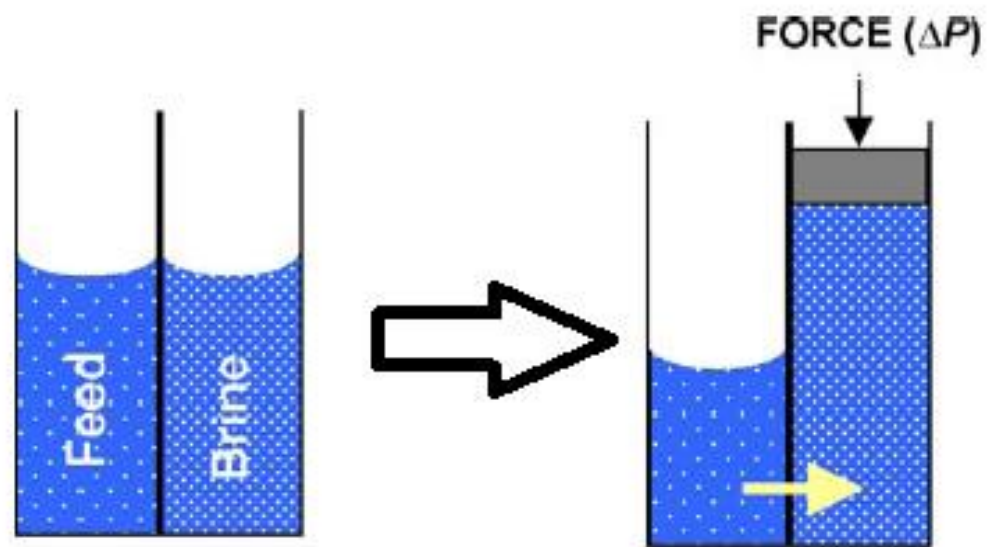


Figure 2-2: Process Model of pressure retarded osmosis (Cath et al., 2006).

### 2.2.3 Reverse Osmosis

According to Peñate (2011), reverse osmosis is the separation of dissolved solids from water by applying a pressure differential across a membrane that is permeable to water but not to the dissolved solids. As it is so aptly named, this process is the exact opposite of the natural phenomena of osmosis. In osmosis, water molecules flow through a semi-permeable membrane from the less concentrated solution to the more concentrated one, without external influence. This flow continues until the internal pressure of both concentrations is equal, creating a zero pressure differential and halting flow. In reverse osmosis, hydraulic pressure is applied to the more concentrated solution (containing dissolved solids) which causes water molecules to flow through a semi-permeable membrane to the dilute solution (without dissolved solids). Besides, as stated by Paul (2004), the membrane, made of either cellulose acetate or polyamide, rejects most of the

solids creating two streams, one of pure water, product or permeate, and one with dissolved solids, concentrate or reject. Figure 2-3 shows the process of reverse osmosis.

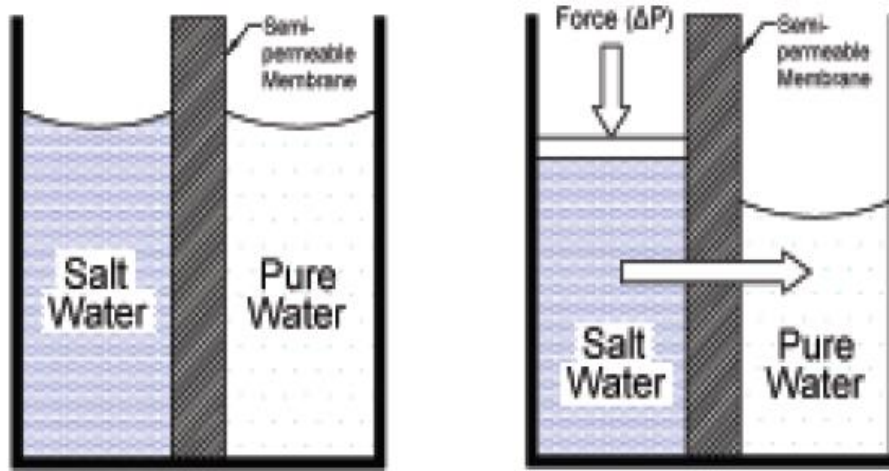


Figure 2-3: Process Model of reverse osmosis (Duranceau, 2012).

#### 2.2.4 Differences between forward osmosis, reverse osmosis and pressure retarded osmosis

The differences between the processes of forward osmosis, pressure retarded osmosis and reversed osmosis can be seen by the water flux and energy consumption of these processes. According to Chou et al. (2012), theoretically, the water flux in an osmosis process can be described as shown in equation (1).

$$J_w = A \times (\Delta\pi - \Delta P) \quad (1)$$

where  $J_w$  is the water flux,  $A$  is the water permeability while  $\Delta\pi$  and  $\Delta P$  is the osmotic and hydrostatic pressure respectively across the semi-permeable membrane. Whereas, also according to Chou et al. (2012), the energy consumption in an osmosis process can be described in the equation as shown in equation (2).

$$W = A \times (\Delta\pi - \Delta P) \times \Delta P \quad (2)$$

where  $W$  is the energy consumption or power density,  $A$  is the water permeability while  $\Delta\pi$  and  $\Delta P$  is the osmotic and hydrostatic pressure respectively across the semi-permeable membrane. The figure below graphically shows the difference between these 3 processes in terms of water flux.

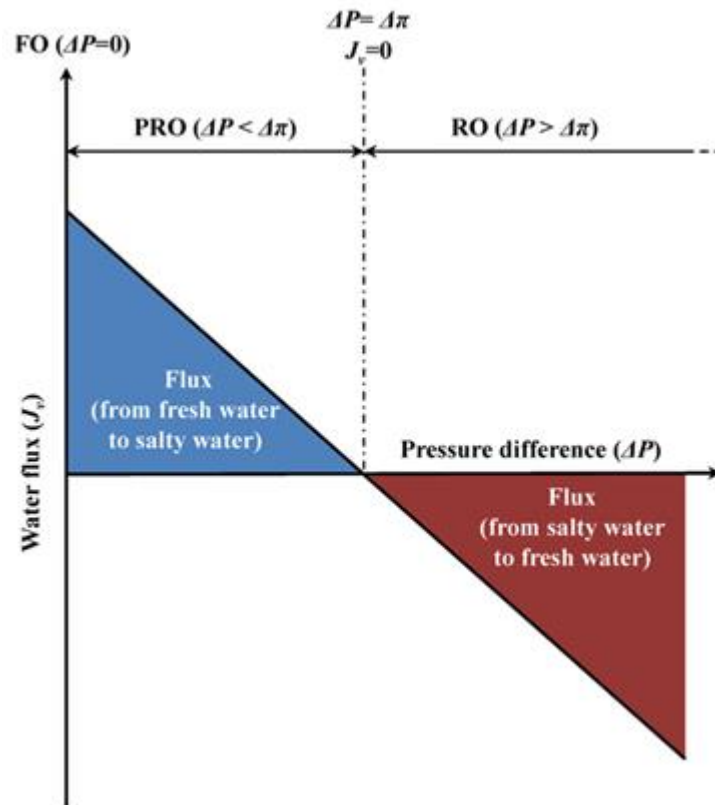


Figure 2-4: Water flux direction of forward osmosis, pressure retarded osmosis and reverse osmosis (Chou et al., 2012).

Based on figure 2-4, it is shown that the process of forward osmosis does not require hydrostatic pressure differential, where  $\Delta P=0$ , to achieve high water flux value. However, as for pressure retarded osmosis, hydrostatic pressure difference across the semi-permeable membrane is needed for the process to occur. Moreover, this graph shows that the hydrostatic pressure in pressure retarded osmosis has to be lower than the osmotic pressure,  $\Delta P < \Delta \pi$ , to provide high water flux which is supported by the concept of pressure retarded osmosis (Loeb & Norman, 1975). On the other hand, for reverse osmosis process, hydrostatic pressure is needed to be higher than osmotic pressure for the process to occur. In addition, based on the graph, the higher the hydrostatic pressure, the higher the water flux; which is supported by the concept of reverse osmosis (Afonso et al., 2004). Hence, it can be concluded that the process of forward osmosis does not require any hydrostatic pressure for the process to occur thus making it the process with the least hydrostatic pressure while the process of reverse osmosis requires the highest hydrostatic pressure to work effectively with high water flux. On the other hand, the

figure 2-5 graphically shows the difference in between the 3 osmotic processes in terms of energy consumption.

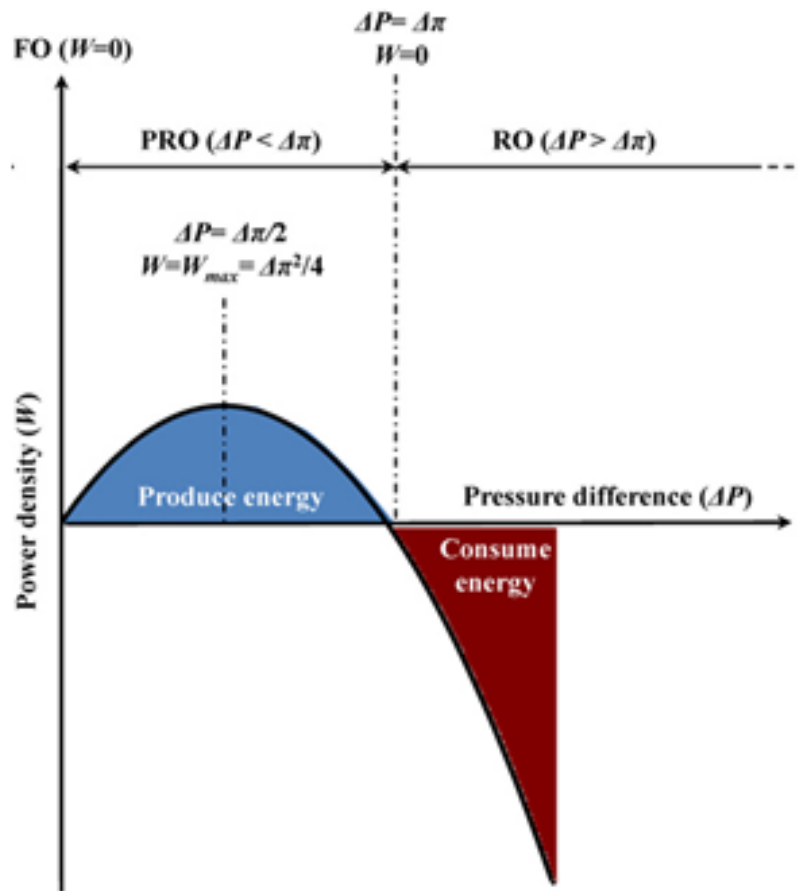


Figure 2-5: Energy consumption/production of forward osmosis, pressure retarded osmosis and reverse osmosis (Chou et al., 2012).

### 2.2.5 Advantages of forward osmosis

Forward osmosis has a range of potential benefits, mainly due to the low hydraulic pressure required by this osmotically driven process. The potential benefits of forward osmosis as used in various water treatment applications are illustrated in figure 2-6. First, forward osmosis holds the promise of helping achieve low energy consumption due not having to supply external forward osmosis or pressure forward osmosis the process to occur, thereby lowering costs, if suitable draw solutes and their regeneration methods can be economically and technically developed (Elimelech & Philip, 2011). This could be one of the most attractive points of forward osmosis, especially under the stress of energy crises. Furthermore, energy can be harvested from the mixing of freshwater and saline water by pressure retarded osmosis (Lee et al., 1981).

According to Achilli et al., (2009), recent studies have demonstrated that membrane fouling in forward osmosis is relatively low and this is supported by which state that the absent of hydraulic pressure in forward osmosis which depends on osmotic gradient reduces the chance of foul material to remain on the surface of membrane, more reversible and can be minimized by optimizing the hydrodynamics (Lee et al., 2010). Additionally, a variety of contaminants can be effectively rejected via the forward osmosis process (Cartinella et al., 2006). Forward osmosis also has the potential to help achieve high water flux and high water recovery due to the high osmotic pressure gradient across the membrane. High water recoveries could help reduce the volume of desalination brine, which is a major environmental concern forward for current desalination plants, particularly for inland desalination (McCutcheon et al., 2005).

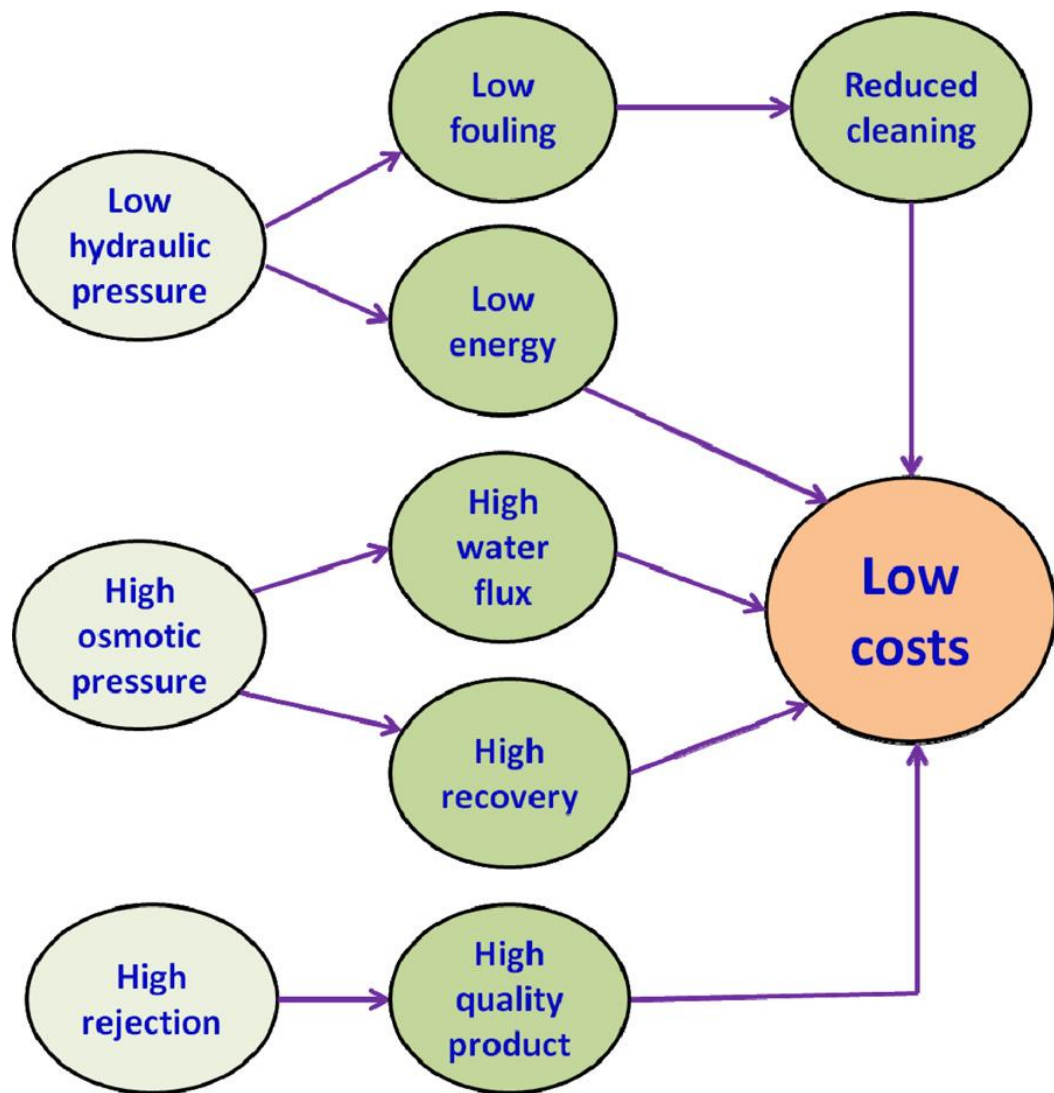


Figure 2-6: Potential benefits of forward osmosis in water treatment (Zhao et al., 2012).